

Ongoing development of a near-surface shear wave velocity (V_s) model for Christchurch using a region-specific CPT- V_s correlation

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ABSTRACT

This paper summarizes the development of a region-wide surficial shear wave velocity model based on the combination of the large high-spatial-density database of cone penetration test (CPT) logs in and around Christchurch, New Zealand and a recently-developed Christchurch-specific empirical correlation between soil shear wave velocity and CPT. The ongoing development of this near-surface shear wave velocity model has applications for site characterization efforts via the development of maps of time-averaged shear wave velocities over specific depths, and the identification of regional similarities and differences in soil shear stiffness.

Keywords: shear wave velocity, cone penetration test (CPT), site characterization

1 INTRODUCTION

The 2010-2011 Canterbury earthquake sequence resulted in widespread damage to the infrastructure of the greater Christchurch urban area (Bradley 2012a, 2012b; Bradley and Cubrinovski 2011; Cubrinovski et al. 2010, 2011a, 2011b). Much of the incurred damage was geotechnical in nature, and as a result, a significant portion of the post-earthquake recovery efforts in Christchurch have involved the characterisation of the near-surface (depth < 30 m) soil conditions in the region. Thousands of subsurface exploration logs obtained through these ongoing recovery efforts have been made available for research purposes through the Canterbury Geotechnical Database project, providing an unparalleled resource in terms of the scope and spatial density of available subsurface data. In this study, the available cone penetration test (CPT) data (> 15000 individual records as of 1 February 2014) is used together with the Christchurch-specific CPT- V_s model of McGann et al. (2014a, 2014b) to develop a set of regional near-surface shear wave velocity (V_s) models that describe the spatial and depth-wise variation of V_s in terms of travel time-averaged shear wave velocities (V_{sz}) for profile depths of $z = 5, 30$ m. This paper represents a summary of work in this area; interested readers are referred to McGann et al. (2014c) for further details.

2 DEVELOPMENT OF REGIONAL SHEAR WAVE VELOCITY MODELS

2.1 Data and assumptions

The CPT data referenced in this report includes 15364 individual CPT records extracted from the Canterbury Geotechnical Database as at 1 February 2014 for sites located throughout Christchurch and the surrounding towns and suburbs. The CPT records in this dataset generally cover the range of depths extending from the ground surface to the upper surface of the Riccarton Gravel that exists beneath Christchurch (Brown and Weeber, 1992) though a large portion of the CPT tests were terminated at a pre-defined target depth (typically 20 m) or upon effective refusal above the Riccarton Gravel. The raw CPT measurement data from the adopted dataset was evaluated for suitability using a series of filters and exclusion criteria to ensure that only sites with consistent and useful data are used in the subsequent analysis and development steps. After the application of these criteria, a total of 10550 CPT sites were retained, i.e., 4818 CPT records were excluded (McGann et al. 2014c).

Shear wave velocity profiles are estimated for each CPT record using the Christchurch-specific CPT- V_s correlation of McGann et al. (2014a, 2014b). These V_s profiles are used to develop surfaces describing the distribution of time-averaged shear wave velocity (V_{sz}) across the Christchurch area. Target profile depths of $z = 5$ and 30 m are presented here to allow for an assessment of soils that are

important in phenomena such as liquefaction (V_{ss}) and an overall assessment of the near-surface zone (V_{s30}) that is commonly used for building-code based site characterization (e.g., BSSC 2003; ASCE 2013). V_{sz} values are computed for each profile depth as

$$V_{sz} = \Sigma(d_i) / \Sigma(d_i/V_{si}) \quad (1)$$

where d_i are CPT depth measurement increments up to the target depth, V_{si} are the mean shear wave velocities over each increment, and Σ indicates the sum over all increments.

Due to the nature of the stratigraphy beneath the Christchurch region, the computation of V_{s30} (time averaged shear wave velocity to 30 m) requires the estimation of the depth to the upper surface of the Riccarton Gravel and volcanic rock surfaces that underlie the surficial sediments (Brown and Weeber, 1992), along with the estimation of the V_s values within these materials. A pair of interpolated surfaces describing the upper boundaries of the Riccarton Gravel and volcanic rock layers have been developed using well log data from about 530 sites in the Canterbury region (Lee et al., 2014) and, for the Riccarton Gravel, the western outcrop of this surface per the GNS QMAP data for the Christchurch area (Forsyth et al., 2008). These surfaces are used to estimate the depth to the top of the Riccarton Gravel or volcanic rock layers at each CPT site. For sites where the CPT termination depth is deeper than the estimated depth to these surfaces, the termination depth is used. Shear wave velocities for the Riccarton Gravel are estimated using the dense gravel reference V_s profile suggested by Lin et al. (2014) and V_s for the volcanic rock is assumed to be a constant 750 m/s. For CPT sites where the depth to one of these surfaces is < 30 m, these assumed gravel and rock velocities are appended to the CPT- V_s profile to get the 30 m deep V_s profiles necessary for the V_{s30} model.

2.2 Spatial interpolation for V_{sz} surfaces

Smooth surfaces of V_{sz} that approximate the CPT-based V_{sz} data points determined using equation (1) were fit to 200 m x 200 m grids. If no CPT record was within 300 metres of a single grid point, then no estimate of V_{sz} was computed at that point. This 300 m boundary distance was selected based on an examination of the spatial variability in the soil profiles, and was enforced to ensure the resulting surfaces focus only on well-constrained estimates as opposed to estimates over the full urban region. Each grid is subdivided according to the surficial geologic units (QMAP units) indicated on the 1:250,000 scale geologic map of Christchurch (Forsyth et al., 2008), and for each target depth, z , the full V_{sz} surface is compiled from separate surfaces fit to the CPT results located in the alluvium, marine/dune, estuarine, and peat/swamp QMAP units to avoid interpolation or extrapolation across surficial geologic boundaries. The surface-fitting procedure uses a modified ridge estimator (Khalaf et al., 2013) that is biased towards smoothness to achieve surfaces that are representative of the trends in the CPT-based results without necessarily representing V_{sz} at any particular site. V_{sz} values on the edges of the interpolated surfaces are naturally less constrained by existing CPT data, and are often based on extrapolation (up to the predefined 300 m boundary distance), thus, such values should be interpreted with a greater degree of uncertainty than values in the middle of the surfaces that are better constrained.

3 REGIONAL V_{s30} MODEL

Figure 1 shows the V_{s30} surface model developed from the aforementioned methodology. Major roads are indicated as black lines and the horizontal and vertical axes indicate the distance in kilometres from the lower-left datum noted in the figure caption. As shown, there is a large degree of spatial variability in V_{s30} , with values varying by about 100-120 m/s across the region. With the exception of some western sites with shallow gravels, there is a general trend of increasing V_{s30} from west to east in CPT-penetrable soils, as the values within the marine/dune QMAP unit located in the east tend to be higher than those in the alluvial, peat/swamp, and estuarine units located further west. The increased velocities in the marine/dune deposits may be due a combination of densification due to wave-action during deposition and the relative lack of fines and plastic soils in these deposits in comparison to the other surficial units. The general band of softer (i.e., low V_{s30}) alluvial sites located between Belfast in the north and the Port Hills in the south in particular have an increased amount of silty and clayey soil relative to the rest of the region. The eastern edge of this soft band, extending southeast from about (17, 20) to (22, 14) in the coordinates noted in Figure 1, roughly corresponds with the coastline that existed approximately 3000 years ago (see Fig. 7, Brown and Weeber, 1992).

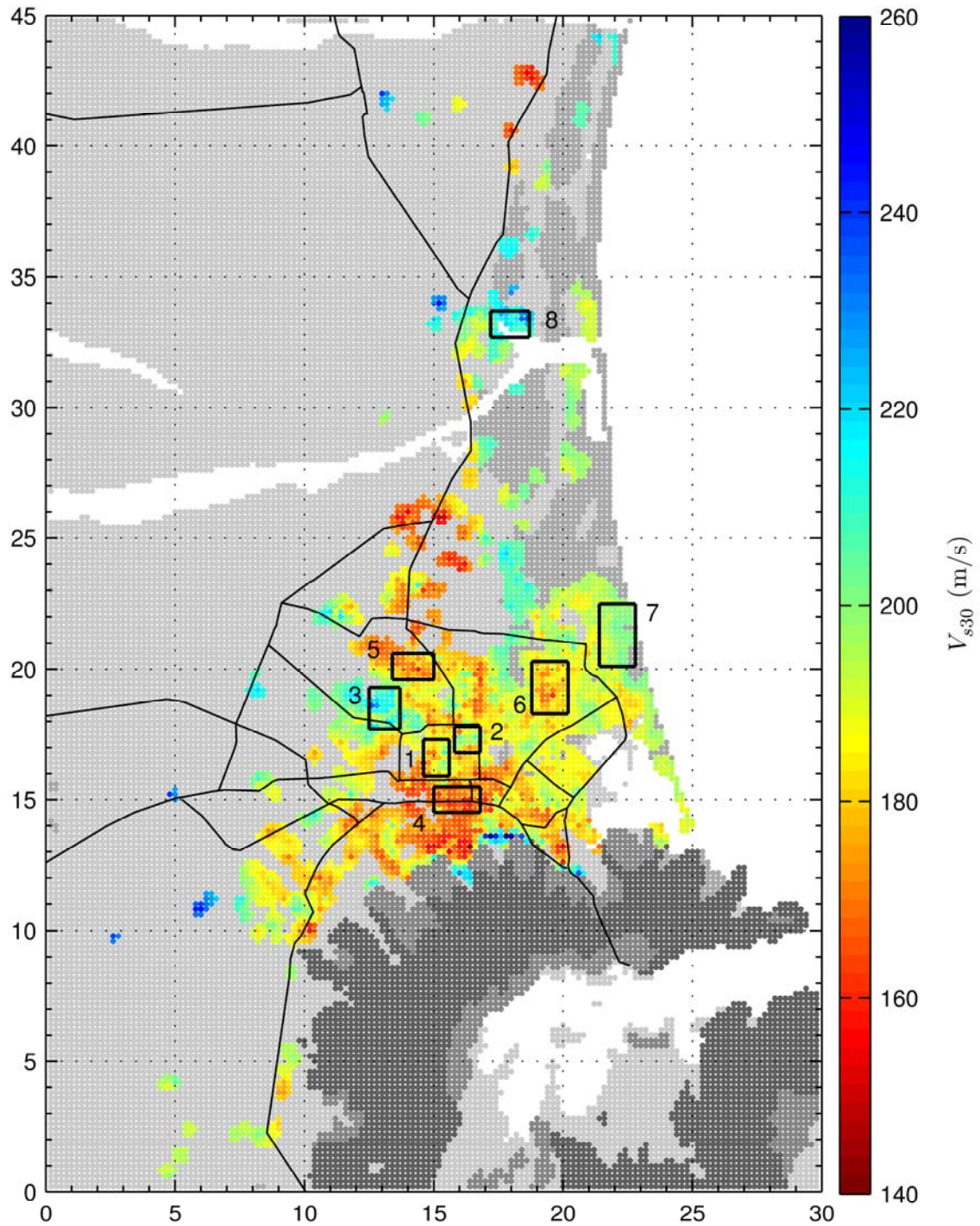


Figure 1. V_{s30} (in m/s) surface on uniform 200 m x 200 m grid. NZMG projection; horizontal and vertical axes indicate km from lower left corner of map. Latitude/Longitude (WGS84) bounds for the map are (-43.6811°, 172.4418°) and (-43.2773°, 172.8151°). Predictions are only provided in each grid cell if there is one or more CPT record within 300 m. The numbered boxes represent specific sub-regions that are examined in more detail in McGann et al. (2014c).

The sites located at the toe of the Port Hills to the south of Christchurch city display some of the highest V_{s30} values for the region, as these sites are generally underlain by volcanic rock at shallow depths ($z < 30$ m), as opposed to the Riccarton Gravels below the remainder of the sites. Other areas that have notably increased values of V_{s30} include the surficial dune sands in the east, which are clearly visible on the coast and the immediate western side of the estuary near Aranui, and some of the Springston Formation over-bank deposit 'lobes' in the western part of the city (Brown and Weeber, 1992). One such lobe is visible as the blue path between Ilam, Merivale, and Bryndwr, while others are notable for their absence from the model (i.e., no CPT data for sites with surficial gravels).

3.1 Site classification from V_{s30}

V_{s30} is widely used for site characterization purposes through the definition of V_{s30} -based site classes, e.g., the United States National Earthquake Hazards Reduction Program (NEHRP) site classes (BSSC, 2003; ASCE, 2013), that dictate various seismic design requirements in building codes. Figure 2 shows the NEHRP site classes inferred from the V_{s30} surface of Figure 1 (without regard for the special conditions for site class F). As shown, the Christchurch sites are characterized as either NEHRP site class D (blue markers) or class E (red markers). The class E sites primarily correspond to known areas of silty, clayey, or swampy soils such as Papanui and Sydenham. There are also a few sporadic zones of class E soils along the path of the Avon river through the eastern suburbs of the city. Because only those CPT sites that penetrated to a useful depth were utilized, and because sites in the loess deposits were omitted during model development, the results of Figure 2 do not depict stiff sites in the Port Hills or western suburbs which may be characterized as NEHRP site classes B or C. It is noted that NZS1170.5 (2004) defines site classes on the basis of V_{s30} as well as other site conditions (site period, compressive strength) and therefore an “NZS1170.5-based map” is not trivial to derive directly from the V_{s30} map developed here.

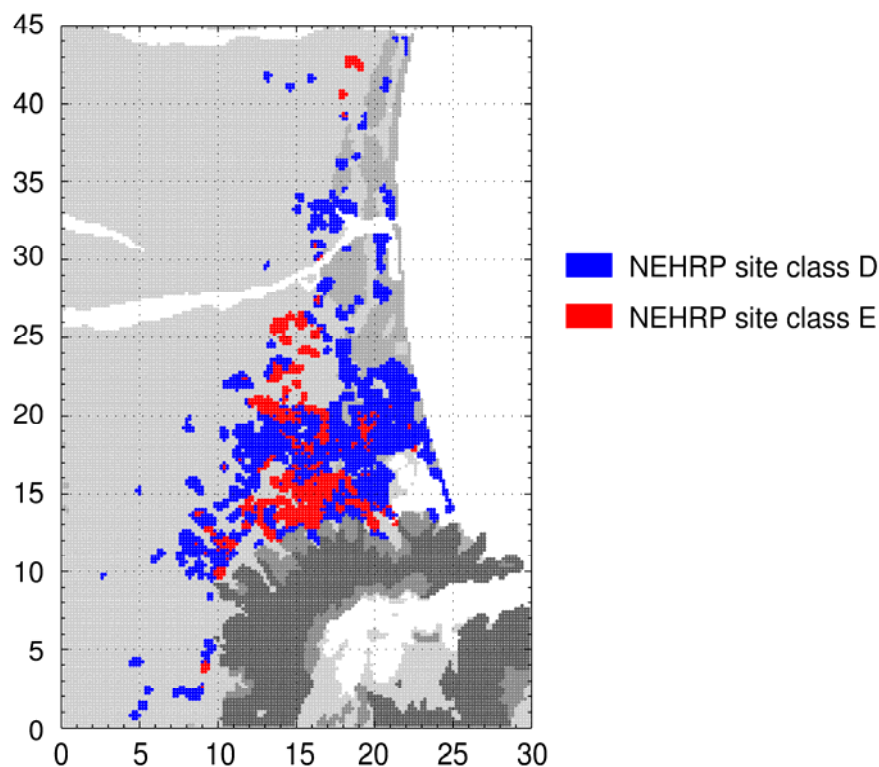


Figure 2. NEHRP site classes for Christchurch V_{s30} surface model. Red markers indicate site class E ($V_{s30} < 180$ m/s) and blue markers indicate site class D ($180 < V_{s30} < 360$ m/s).

4 REGIONAL V_{s5} MODEL

Figure 3 shows the surface model developed for V_{s5} . While the V_{s30} surface map shown in Figure 1 provides general insights on overall site response and can be used for rough site classification purposes, surfaces for shallower target profile depths such as V_{s5} can provide insights into different aspects of the expected site response at a given location. Because V_{s5} provides a description of the soils in the range of depths at which liquefaction commonly occurs, one such aspect that is of particular interest in Christchurch is insight into the liquefaction response of a given location or a particular region, especially when interpreted in the context of known features of the soil composition, behaviour type, or geologic history.

The strong shaking associated with the events of the 2010-2011 Canterbury earthquake sequence triggered extensive liquefaction in the Christchurch area. As shown in the residential liquefaction-induced land damage map in Figure 4 (van Ballegooy et al., 2014), the surface manifestations and damage associated with this liquefaction were particularly severe in the suburbs to the east and

immediate north of the central business district (CBD) near the present-day route of the Avon river. The V_{s5} model shown in Figure 3 corresponds well with the liquefaction damage map, with areas where liquefaction occurred typically displaying lower V_{s5} values than surrounding areas where liquefaction was not observed. For example, the boundary between the yellow and yellow-green markers ($V_{s5} \leq 105$ m/s) and the light blue markers ($V_{s5} \geq 115$ m/s) in the eastern suburbs near the Avon river roughly approximate the damage/no damage boundaries reported by van Ballegooy et al. (2014) and shown in Figure 4, and delineates the liquefaction-susceptible alluvial soils that follow the path of the Avon river from the marine/dune deposits in which severe liquefaction was more rarely observed.

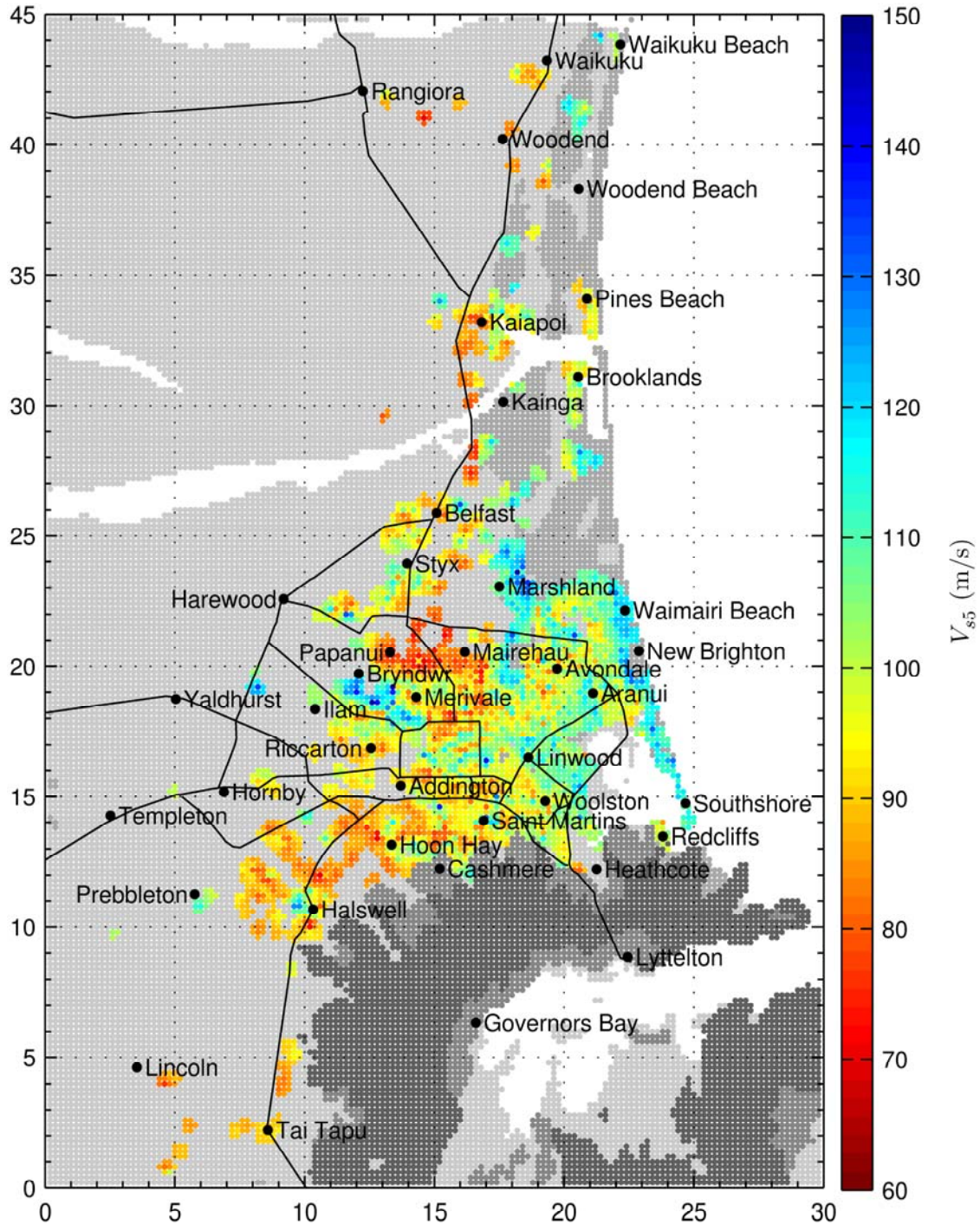


Figure 3. V_{s5} (in m/s) surface on uniform 200 m x 200 m grid. NZMG projection; horizontal and vertical axes indicate km from lower left corner of map. Latitude/Longitude (WGS84) bounds for the map are $(-43.6811^\circ, 172.4418^\circ)$ and $(-43.2773^\circ, 172.8151^\circ)$. Predictions are only provided in each grid cell if there is one or more CPT record within 300 m.

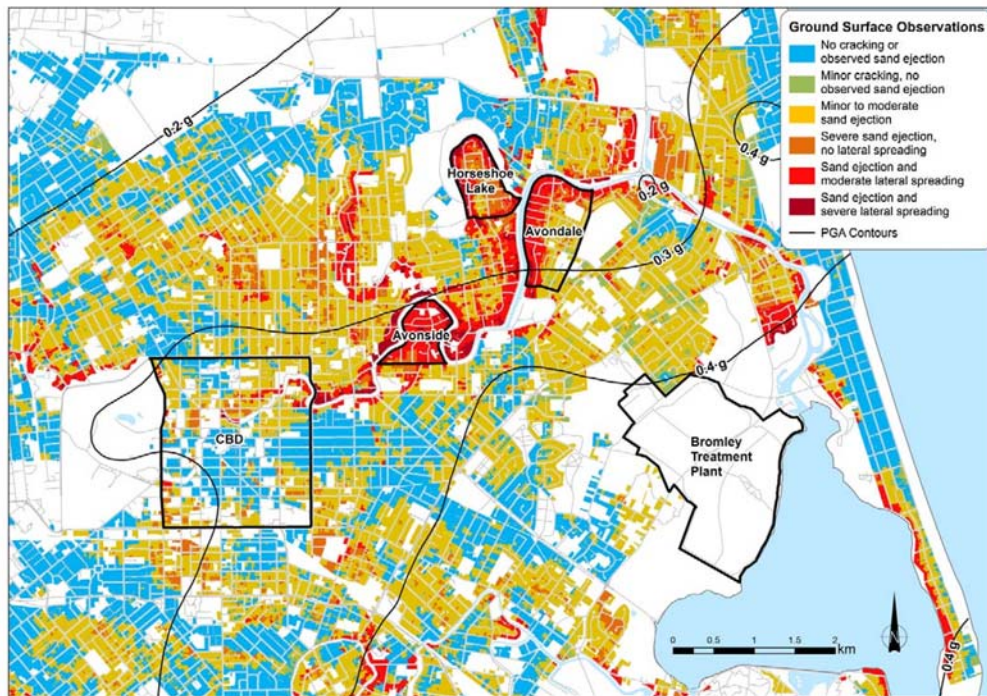


Figure 4. Liquefaction-induced land damage map for central and eastern areas of Christchurch following the February 2011 earthquake after van Ballegooy et al, (2014).

The very soft locations indicated in Figure 3 (orange and red with $V_{s5} \leq 85$ m/s) are, perhaps counter-intuitively, primarily areas where liquefaction was not observed following the 2010-2011 earthquakes. This is likely due to the nature of the soils in these regions. For example, in the soft zones located in the Papanui/Mairehau and Sydenham areas, soils in the upper 5-10 m are comprised primarily of silts, clays, and silty sands. While the predominance of these types of soils at shallow depths results in low values of V_{s5} (and even V_{s30}), these areas do not correspond to liquefaction observations, as these types of soils are either less susceptible to liquefaction or not liquefiable because of their composition. These regions of low V_{s5} values are highly correlated with locations of in-filled swamps, lagoons, and other current or formerly wet areas depicted in Figure 5 as inferred from the 1856 'black maps' of Christchurch (Wilson, 1989).

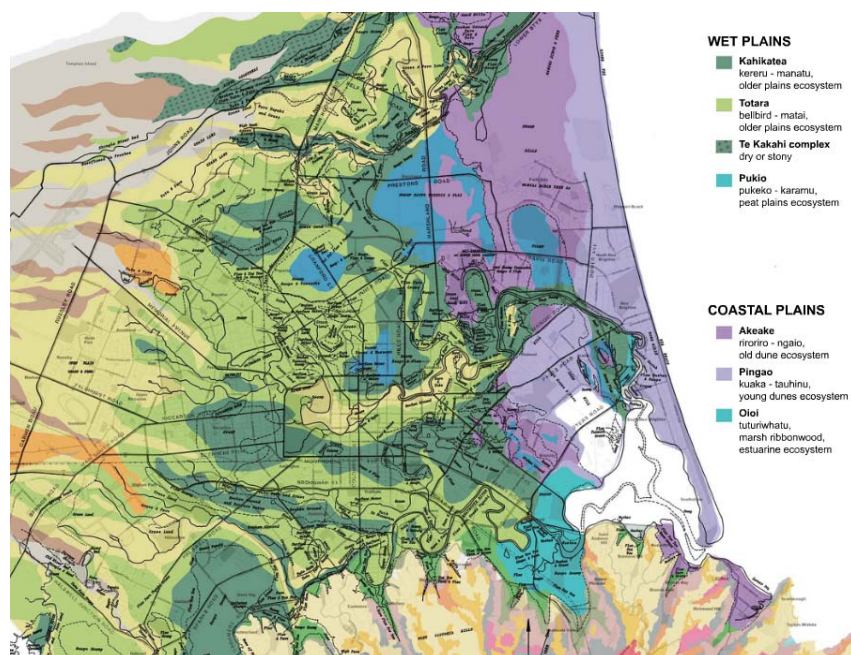


Figure 5. Locations of wet areas inferred from 1856 black maps of Christchurch after Lucas Associates (2014).

As mentioned in the previous discussion of the V_{s30} model results, the areas of higher V_{s5} (and areas of missing CPT data) correlate well with overbank gravel lobes of the Springston Formation. Figure 6 shows a map Christchurch that indicates the dominant surficial geology of the region (Brown and Weeber, 1992). As shown, the overbank gravel deposits (areas with gravel ≤ 1 m below the surface) are prevalent to the west of Christchurch, and there are several lobes that extend east to approximately the western edge of Hagley park. The northern-most overbank gravel lobe (labelled as *a* in Figure 6) corresponds well with the V_{s5} model; in the area of Bryndwr the V_{s5} values are notably higher than the surrounding regions. The remaining gravel lobes indicated by Figure 6 (*b*, at the southwest corner of the CBD; and *c* extending towards the Port Hills between Halswell and Hoon Hay) correspond reasonably well with areas not represented by the V_{s5} model due to lack of available CPT data (i.e., no CPT penetration possible, or very shallow termination depth in gravel-dominated soils). The other areas in which there is a distinct lack of CPT data likely correspond to soils that are similarly dominated by gravels at shallow depths, or rural areas where no critical damage was observed following the 2010-2011 earthquakes due to a lack of infrastructure.

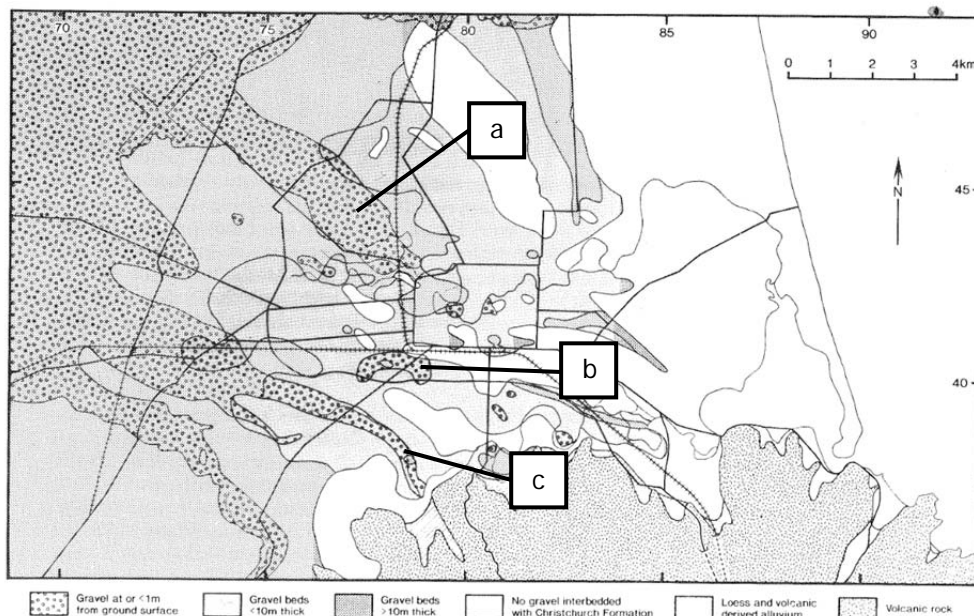


Figure 6. Dominant surficial geologic deposits in Christchurch area after Brown and Weeber (1992).

5 CONCLUSION

The Christchurch-specific CPT- V_s correlation of McGann et al. (2014a, 2014b) was applied to the large, high-spatial density CPT dataset (> 15000 considered CPT logs), made available through the Canterbury Geotechnical Database, to create regional models of time-averaged shear wave velocity for profile depths of 5 and 30 metres (V_{s5} and V_{s30} , respectively). These regional shear wave velocity models provide well-constrained estimates of V_{s5} and V_{s30} on uniform 200×200 metre grids in which edge extrapolation is not permitted further than 300 m from a single CPT location. The variation in V_{s5} and V_{s30} observed in these models demonstrates the variety of near-surface soil conditions present in the Christchurch area. Much of this regional variation is consistent with several known historical and geological features. The portions of the model surfaces with the lowest V_{s5} and V_{s30} values correlate well with current and former wet or swampy regions where the near-surface soil profiles are characterized by silts, clays, and peats. The portions of the models with the highest V_{s5} values, as well as many western portions of the models where no CPT data was available, correlate well with known areas of gravel-dominated shallows soils. When compared with post-earthquake liquefaction-induced damage observations, the V_{s5} model demonstrated a marked difference in inferred soil shear stiffness in the upper 5 metres for areas which incurred significant damage as compared to adjacent regions with less severe liquefaction-related damage. Despite this apparent correlation, it is important to note that the V_{s5} model alone cannot be used for the identification of liquefaction-susceptible soils as the soil composition is an important factor not captured by shear wave velocity. Further details on this study are provided in McGann et al. (2014c).

6 ACKNOWLEDGEMENTS

Funding for this work was provided by the New Zealand Earthquake Commission (EQC) and the Natural Hazards Research Platform (NHRP). The authors would also like to thank the Canterbury Geotechnical Database team for providing access to the data used in this study.

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